# SECTION 6

# MANNING'S n VALUE AND VELOCITY MEASUREMENTS

One objective of the Biofiltration Project was to measure the Manning's n value in the field, while the swale was operating within design flows. The swale monitored for this pollutant removal study was found to have two different longitudinal slopes. The study was, then, also able to determine if the two slopes had an effect on the observed Manning's n value.

## EXPERIMENTAL DESIGN

Manning's Equation predicts the velocity (V) of water flowing through a conveyance channel by considering the slope (s), the hydraulic radius (R) and n, a factor related to roughness or friction. The equation is as follows:

$$V = \frac{1.486}{n} * R^{2/3} * s^{1/2}$$

If the velocity of the flow is known, and the slope and hydraulic radius can also be measured, the same equation can be used to calculate the n value. This logic was, then, pursued to determine the Manning's n for the swale. A set of measurements was designed to determine both the velocity and the depth of flow in the swale. These data, along with the hydraulic radius and slope, would then provide sufficient information to determine the Manning's n value.

The hydraulic radius is a geometric parameter equal to the cross sectional area divided by the wetted perimeter. If the water depth and swale dimensions are known, it can be readily calculated. The slope was determined by survey, and found to be different in the upper and lower portions. The slope change was approximately midway through the swale, 90 feet from the upper H-flume. The upper slope was 3.6 percent; the lower slope 4.3 percent.

Velocity and depth measurements were made on two occasions, once before and once after the grass was mowed in October. The first set of measurements was taken September 10, 1991, when the grass was approximately 1 foot high. A second set was taken on October 21, 1991, after the grass had been mowed to about 6 inches, and field techniques had been refined.

## MATERIALS AND METHODS

### Field Methods

Survey control was installed for each of the two slopes. Survey hubs (2 inches by 2 inches by 6 inches) were used to indicate locations for velocity and depth measurements. Hubs were driven flush to the ground surface in a grid, 6 rows across (parallel to the flow) and three down (perpendicular to the flow). Above and below this grid, three hubs were installed for vertical survey control. Figures 6-1a and 6-1b show the layout of the upper and lower swale sections.

A fire hose conveyed water from a nearby fire hydrant to a catch basin immediately upstream from the swale. Flow was regulated using the fire hydrant valve and monitored using a utility meter with an accuracy of plus or minus 30 percent. The meter provided the nominal flow reading for identifying the three flow rates for the trials.

The water was allowed to run through the swale for about an hour to saturate the ground beneath and around the bottom and sides of the swale. Because the swale was not far above an impermeable layer of glacial till, this wetting was considered adequate to prevent significant infiltration losses during the trials. Water depths were measured in the upstream and downstream H-flumes and agreed well, which verified this assumption.

Velocity measurements were made using two Marsh-McBirney model 201 velocity meters. The meters did not agree to a given velocity when placed in the flume, and could only be recalibrated by returning them to the manufacturer. Therefore, the readings of the meters at each hub were not averaged but kept separate. Velocity measurements were taken as the 6-second-average from the meter's digital display. Depth measurements were made to the nearest 0.01 foot from the top of the hub using engineer's tape. Two separate teams made the velocity and depth observations simultaneously, each beginning at a different swale section.

The inflow and outflow volumes through the H-flumes were accurately measured using a variable resistance depth gauge and recorded using a Unidata data logger. The Unidata manufacturer's information indicates an accuracy of plus or minus 5 percent for depth measurements.

For the second trial on October 21, a third team determined maximum velocities in the swale by clocking the travel time of dye passing through the swale.

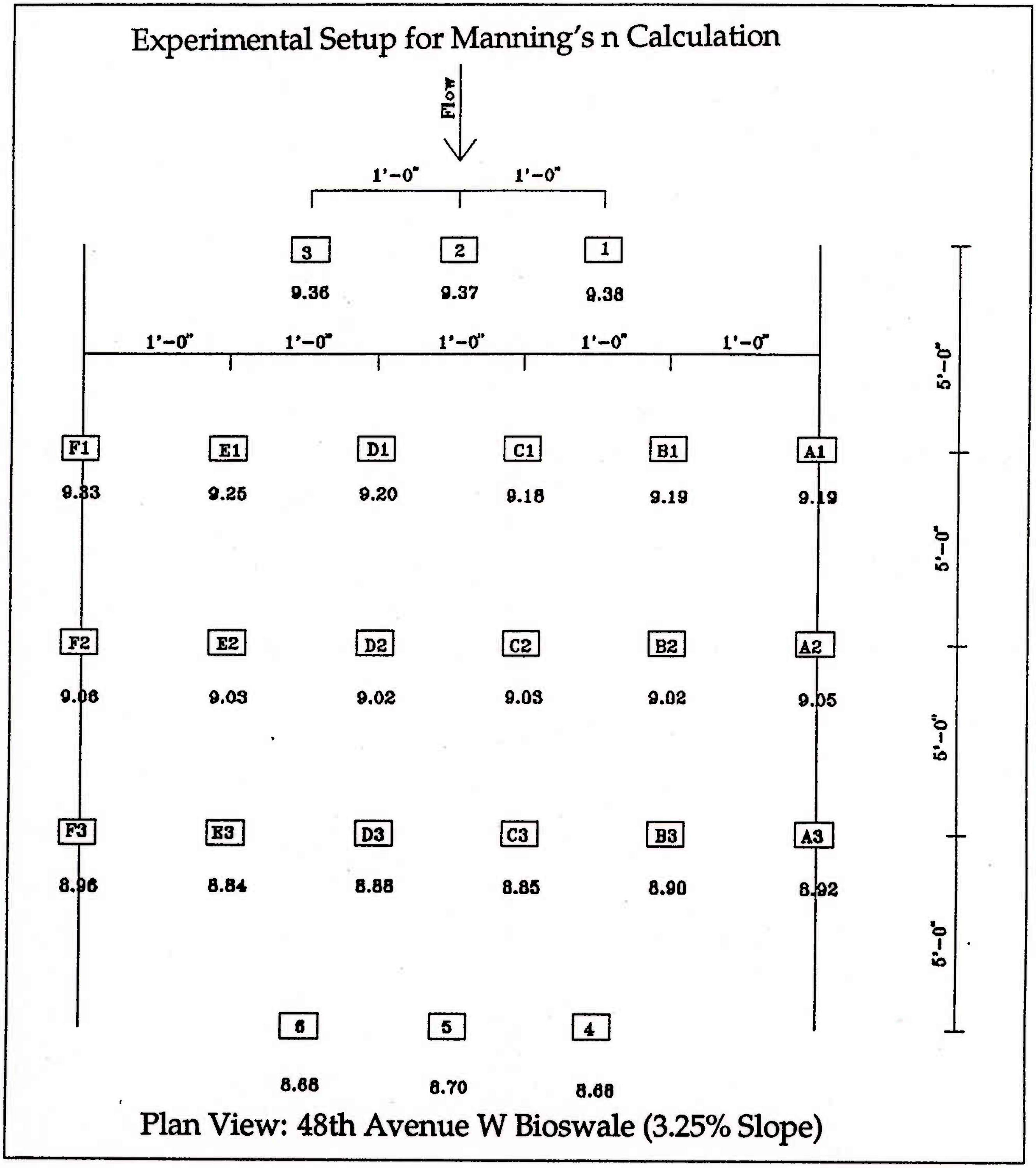


**Figure 6-1a. Experimental Setup for Velocity Measurement**

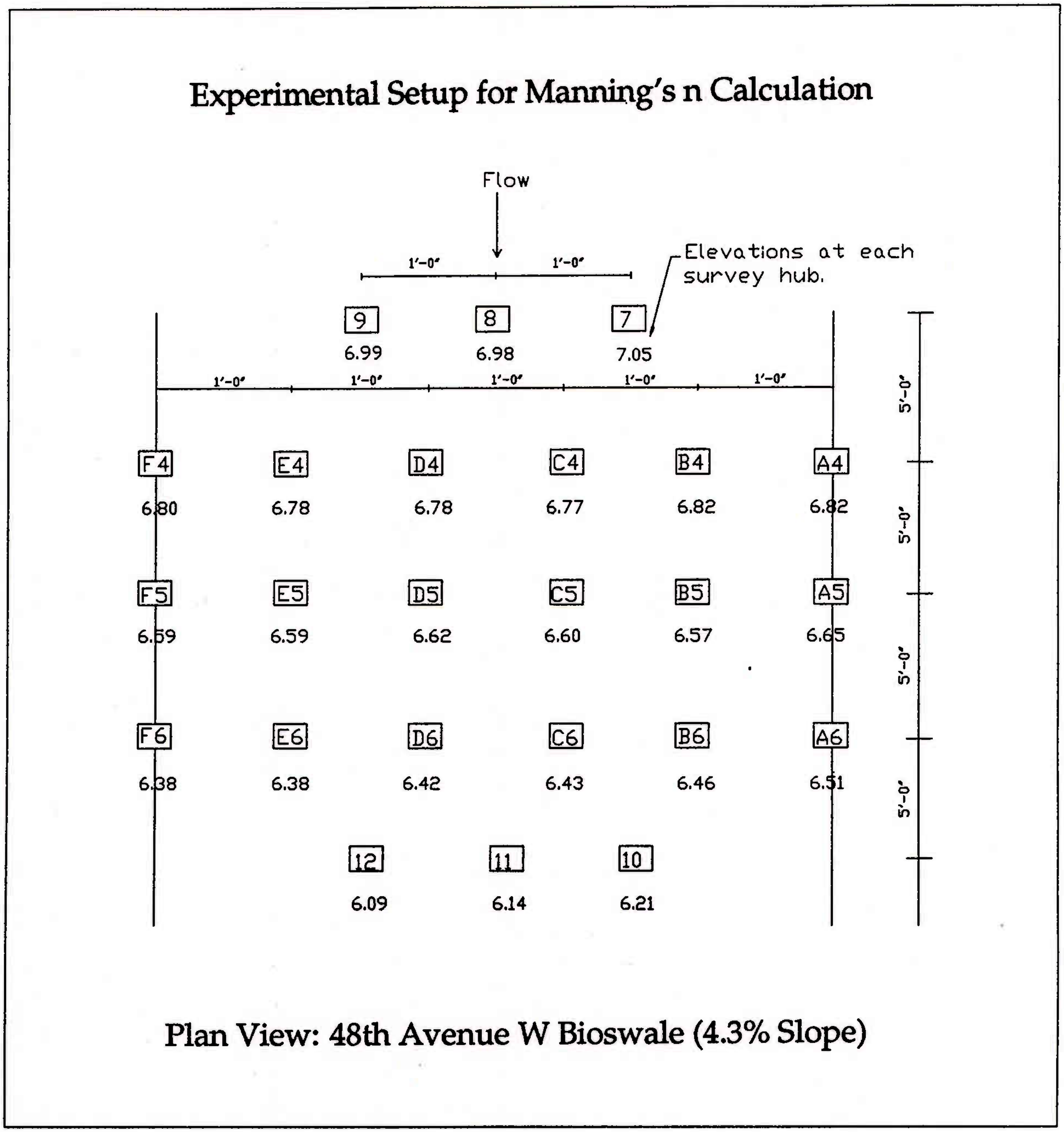


**Figure 6-1b. Experimental Setup for Velocity Measurement**

### Trial 1—September 10, 1991

The first trial was on September 10, 1991 when grass was approximately 12 inches. During most of the trial, however, the grass was bent over, with the flow passing over the grass. Two problems contributed to this situation. First, the field teams stood in the swale to measure depth and velocity at each of the hubs, which flattened the grass in the areas of measurement, resulting in atypical grass performance

Secondly, because of the insensitivity of the hydrant valve, the flow was increased too quickly, causing additional flattening of the grass

Only two flow rates were applied during this trial, 350 gallons per minute (gpm) and 620 gpm as indicated on the hydrant meter. As determined from the data logger, which was more accurate, these rates were actually 0.55 cfs and 1.1 cfs.

Although these data do not represent the optimum design condition in which design storm flow remains below the height of the vegetation, they do represent high flow conditions in an unmaintained swale. These data will be analyzed in the next section following discussion of data for the maintained swale condition.

***Knockdown velocity.*** During the September 10, 1991 trial, it was observed that grass was flattened, rather than merely bent, when the flow was increased from the 0.6 cfs to the 1.1 cfs trial. The flow rate when flattening occurred was measured with the velocity meter and corrected using the calibration curve given in Figure 6-2. This knockdown velocity was 0.93 feet per second.

### Trial 2—October 21, 1991

The October 21, 1991 data measurements were performed after the grass was mowed and approximately 6 inches. For this trial, teams used 12 foot planks as bridges while taking velocity and depth measurements to avoid the previous problems with flattening the grass. Water was introduced into the swale about an hour prior to taking measurements as before to saturate the ground and prevent water loss due to infiltration, as before. Dye velocity tests were also made on this date.

Three flow rates were applied in this trial: 250 gpm, 300 gpm, and 350 gpm according to the hydrant meter. These nominal flow rates, as calculated from the data logger, were actually 0.33, 0.42, and 0.51 cfs. Water depth was about 2.5 inches for the highest flow tested.

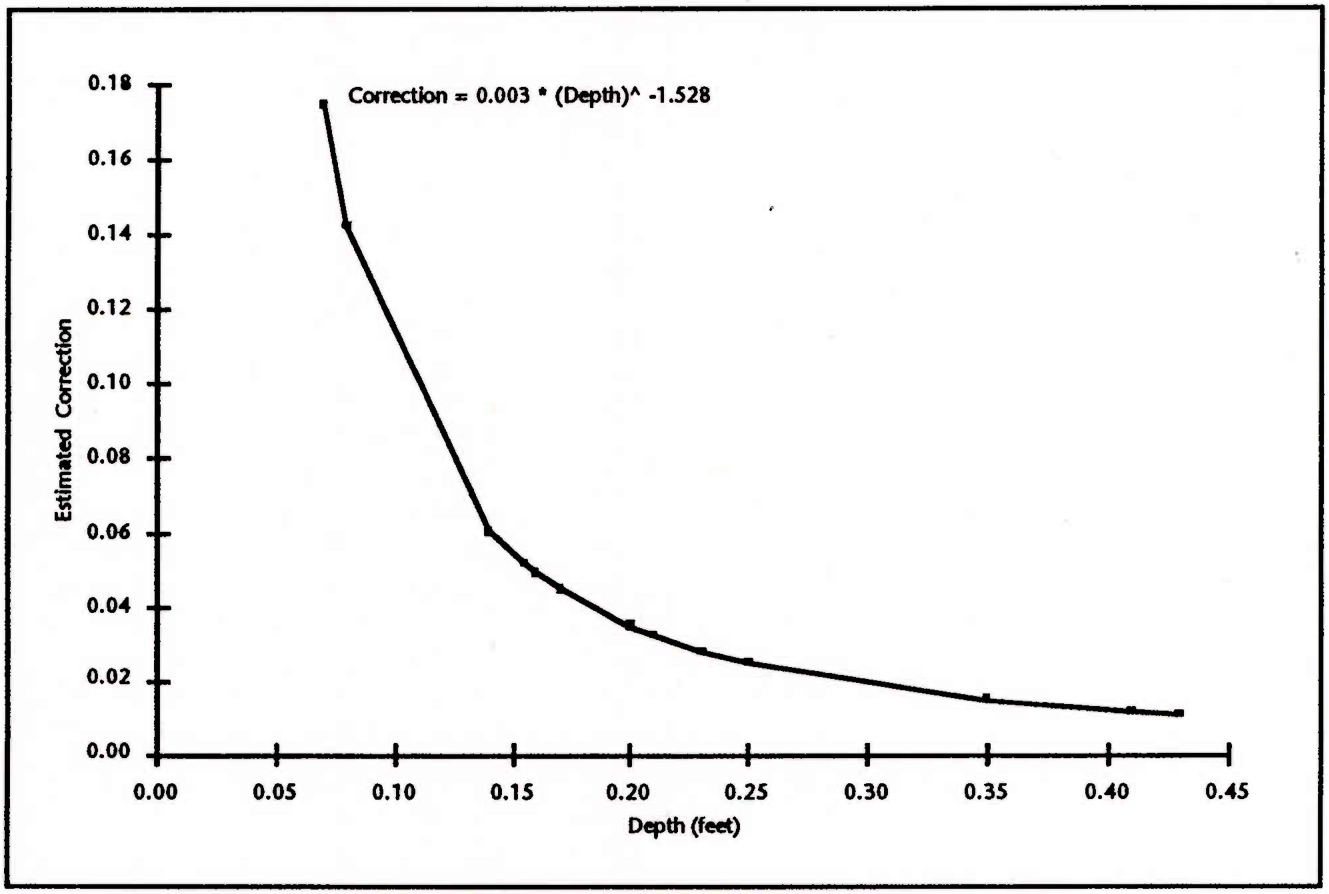


**Figure 6-2. King County Velocity Meter Calibration Curve**

Grass blade density measurements were made the day prior to the trial for possible application of the Barfield design approach, which uses data on grass blade spacing (Minton, personal communication). Densities of 1,600 blades/ft$^2$ and 1,300 blades/ft$^2$ were measured in the middle and lower swale, respectively. The upper swale had densities of 600 blades/ft$^2$. Detailed information on this and other aspects of the Manning's n determination are given in Appendix F.

### Analysis Methods

The following three methods of analyses were used:

1. Use of discharge measurements from the data logger to determine velocity using the relationship V = Q/A
2. Use of incremental velocity and slope measurements, with velocities read from the Marsh-McBurney meters
3. Use of maximum velocities determined from the dye test.

The calculations used the following definitions and relationships:

Q = flow as measured by the data logger at each H-flume (in cfs)

Y = depth of water at a given measuring point (in feet)

V = flow velocity (in feet/second)

A = cross-sectional area of flow (in $ft^2$)

R = hydraulic radius of the conveyance channel (in feet), 3:1 side slopes of the trapezoidal channel were used, calculated by dividing the area (A) by the wetted perimeter (P) of the cross section

P = wetted perimeter of the area A (in feet)

n = Manning's n (dimensionless)

s = slope of the flow path or slope of the swale; ratio of vertical rise to horizontal run (dimensionless)

where:

$Q = V * A$ and

$$V = \frac{1.486}{n} * R^{2/3} * s^{1/2}$$

***Method 1: Use of discharge measurements from the data logger.*** Because the velocity data had limited accuracy for water depths less than 3 inches, Method 1 did not use the data from the velocity meters to calculate Manning's n. Instead, this method used discharge data (Q) from the data logger and water depth as measured for the hub locations. This method solved for Manning's n by using the following relationships:

$$n = \frac{1.486}{Q/A} * R^{2/3} * s^{1/2}$$

The total area A was obtained by determining the incremental depth for each of the grid locations and adding them. The R value was calculated from the A value and the measured wetted perimeter (P). The slope (s) was obtained by averaging the 18 survey elevations for each swale section. These calculations yielded six Manning's n values, one for each transect, for each flow rate.

As a check, the overall flow (Q) was estimated by adding up the six qs calculated using the cross-sectional area and velocity from one of the Marsh-McBirney velocity meters for each of the six hub locations. The Q value calculated using this check did not agree well with the Q value from the data logger, except for the highest flow condition. It is emphasized that this method did not use the velocity meter readings to calculate the Manning's n, but only in the calculation check.

*Method 2: Use of incremental velocity meter and slope data.* This method used the depth, velocity, and slope obtained at each of the hubs to determine the value of n. It is a more cumbersome method, but has the advantage of being usable in other swales without having to install a flow measuring device (for example, the data logger and H-flumes). This method is, however, limited by the inability of the Marsh-McBirney meter to read velocities accurately at low water depths.

The term "incremental" slope, depth, and velocity refers to the value of these parameters at each hub location, rather than the value which represents the average swale environment. The experimental layout for gathering data is presented in Table 6-1.

In calculating the swale information to derive A and R, a hypothetical cell 1-foot by 5-feet was imagined. These imaginary cells put each measuring hub (for incremental velocity and depth data) in the center of a 1-foot-wide cell. The side walls were assumed to be vertical to simplify calculations.

The incremental slope (s) of the channel were derived using the elevation and distance of the hub in the center of the hypothetical cell and the hub elevation and distance immediately upstream and downstream from the cell. The elevations of the adjacent hubs along the cross section were not used. For example, to determine the incremental s value for hub B2, slope information from hubs B1 and B3 was used, but slope information from A2 or C2 was not used. The incremental s value for hub C3 used the slopes to hubs C2 and the nearest vertical control hub.

The V value was obtained from the velocity meters. The meters were not able to read velocities at depths less than 0.08 feet ($Y < 0.08$ feet). The velocity meter from King County Surface Water Management was found to be the more accurate of the two when compared to information from the data logger, so only the velocity data from that meter was used in the analysis to determine n.

The depth and velocity measurements were used selectively. The data from hubs at the side wall slope break (rows A1-A3, A4-A6, F1-F3, F4-F6) were not used because there was only one slope obtainable. Raw data and computations are given in Appendix F.

## Table 6-1. Schematic Layout of Hubs Showing Local Distances, Elevations, and Slopes for Upper and Lower Swales

### UPPER SWALE

**A. Hub Layout by Name**

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3 | | | | 2 | | | | 1 | | | |
| F1 | E1 | | | | D1 | | | | C1 | | | | B1 | A1 |
| F2 | E2 | | | | D2 | | | | C2 | | | | B2 | A2 |
| F3 | E3 | | | | D3 | | | | C3 | | | | B3 | A3 |
| | | | 6 | | | | 5 | | | | 4 | | | |

**B. Hub Pairs Used for Slope Determination**

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 3:6 | | | | 2:5 | | | | 1:4 | | | |
| 0 | | E1:3 | | 3:D1 | | D1:2 | | 2:C1 | | C1:1 | | 1:B1 | | 0 |
| F1:F2 | E1:E2 | | | | D1:D2 | | | | C1:C2 | | | | B1:B2 | A1:A2 |
| F2:F3 | E2:E3 | | | | D2:D3 | | | | C2:C3 | | | | B2:B3 | A2:A3 |
| | | E3:6 | | 6:D3 | | D3:5 | | 5:C3 | | C3:4 | | 4:B3 | | |
| | | | 3:6 | | | | 2:5 | | | | 1:4 | | | |

**C. Elevations Obtained from Level Survey**

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 9.36 | | | | 9.37 | | | | 9.38 | | | |
| 9.83 | 9.25 | | | | 9.20 | | | | 9.18 | | | | 9.19 | 9.19 |
| 9.06 | 9.03 | | | | 9.02 | | | | 9.03 | | | | 9.02 | 9.05 |
| 8.96 | 8.84 | | | | 8.88 | | | | 8.85 | | | | 8.90 | 8.92 |
| | | | 8.66 | | | | 8.70 | | | | 8.66 | | | |

**D. Distances to Upslope Hub**

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0.00 | | | | 0.00 | | | | 0.00 | | | |
| 0.00 | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | 0.00 |
| 5.00 | 5.00 | | | | 5.00 | | | | 5.00 | | | | 5.00 | 5.00 |
| 5.00 | 5.00 | | | | 5.00 | | | | 5.00 | | | | 5.00 | 5.00 |
| | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | |
| | | | 21.00 | | | | 21.00 | | | | 21.00 | | | |

**E. Slopes to Nearest Upslope Hub**

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0.032 | | | | 0.032 | | | | 0.033 | | | |
| | | 0.022 | | 0.032 | | 0.034 | | 0.038 | | 0.040 | | 0.038 | | |
| 0.154 | 0.044 | | | | 0.036 | | | | 0.030 | | | | 0.034 | 0.028 |
| 0.020 | 0.038 | | | | 0.028 | | | | 0.036 | | | | 0.024 | 0.026 |
| | | 0.036 | | 0.044 | | 0.036 | | 0.030 | | 0.038 | | 0.048 | | |
| | | | 0.032 | | | | 0.032 | | | | 0.033 | | | |

### LOWER SWALE

**A. Hub Layout by Name**

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 9 | | | | 87 | | | | 7 | | | |
| F4 | E1 | | | | D4 | | | | C4 | | | | B4 | A4 |
| F5 | E2 | | | | D5 | | | | C5 | | | | B5 | A5 |
| F6 | E3 | | | | D6 | | | | C6 | | | | B6 | A6 |
| | | | 12 | | | | 11 | | | | 10 | | | |

**Table 6-1. Schematic Layout of Hubs Showing Local Distances, Elevations, and Slopes for Upper and Lower Swales (continued)**

LOWER SWALE (continued)

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **B. Hub Pairs Used for Slope Determination** | | | | | | | | | | | | | | |
| | | | 9:12 | | | | 8:11 | | | | 7:10 | | | |
| 0 | | E4:9 | | 9:D4 | | D4:8 | | 8:C4 | | C4:7 | | 7:B4 | | 0 |
| F4:F5 | E4:E5 | | | | D4:D5 | | | | C4:C5 | | | | B4:B5 | A4:A5 |
| F5:F6 | E5:E6 | | | | D5:D6 | | | | C5:C6 | | | | B5:B6 | A5:A6 |
| | | E6:9 | | 9:D6 | | D6:8 | | 11:C6 | | C6:10 | | 10:B6 | | |
| | | | 9:12 | | | | 8:11 | | | | 7:10 | | | |
| **C. Elevations Obtained from Level Survey** | | | | | | | | | | | | | | |
| | | | 6.99 | | | | 6.98 | | | | 7.05 | | | |
| 6.80 | 6.78 | | | | 6.78 | | | | 6.77 | | | | 6.82 | 6.82 |
| 6.59 | 6.59 | | | | 6.62 | | | | 6.60 | | | | 6.57 | 6.65 |
| 6.38 | 6.38 | | | | 6.42 | | | | 6.43 | | | | 6.46 | 6.51 |
| | | | 6.09 | | | | 6.14 | | | | 6.21 | | | |
| **D. Distances to Upslope Hub** | | | | | | | | | | | | | | |
| | | | 0.00 | | | | 0.00 | | | | 0.00 | | | |
| 0.00 | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | 0.00 |
| 5.00 | 5.00 | | | | 5.00 | | | | 5.00 | | | | 5.00 | 5.00 |
| 5.00 | 5.00 | | | | 5.00 | | | | 5.00 | | | | 5.00 | 5.00 |
| | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | 5.025 | | |
| | | | 20.00 | | | | 20.00 | | | | 20.00 | | | |
| **E. Slopes to Nearest Upslope Hub** | | | | | | | | | | | | | | |
| | | | 0.045 | | | | 0.042 | | | | 0.042 | | | |
| | | 0.042 | | 0.042 | | 0.040 | | 0.042 | | 0.056 | | 0.046 | | |
| 0.042 | 0.038 | | | | 0.032 | | | | 0.034 | | | | 0.050 | 0.034 |
| 0.042 | 0.042 | | | | 0.040 | | | | 0.034 | | | | 0.022 | 0.028 |
| | | 0.058 | | 0.066 | | 0.056 | | 0.058 | | 0.044 | | 0.050 | | |
| | | | 0.045 | | | | 0.042 | | | | 0.042 | | | |

Because of discrepancies determined during field tests, velocity meters were taken to the Harris Hydraulics Laboratory test flume at the University of Washington (Seattle, Washington) after the field trials were completed. Accuracy was found to be best for depths greater than 0.15 feet. A correction curve, shown in Figure 6-2 was developed for each meter. The curve was derived by using dye and different water depths in the flume, checking meter readings against known velocities. The velocities recorded in the field were then corrected using this curve.

***Method 3: Use of dye test maximum velocity.*** The velocity determined from the field dye test was also used as a check in determining an upper value for Manning's n. The dye test was only done for two flow trials, the 0.33 cfs and 0.51 cfs flow rates.

## RESULTS AND DISCUSSION

Manning's n values will be presented using the three methods discussed above for data from the October 21 trial where grass height was 6 inches. These data are considered representative of conditions where grass is mowed infrequently during the growing season, and where flow depths are less than half the grass height. Following these analyses, results for the unmowed swale condition (September 10) will be discussed.

### Method 1 Results—Discharge Data from Data Logger and Depth ( 6-Inch Grass Height)

Table 6-2 shows the ranges of depth and flow measurements collected for the three flow rates for the October 21, 1991 trial. Measurements from only one of the velocity meters are given. The Manning's n values calculated using Method 1 are given in Table 6-3. Depth measurements made by both field teams provided valid data, and so are presented. Table 6-4 summarizes the Manning's n values for the two different teams for each of the three flow rates. The average n value for the 3.25 percent slope was 0.166 (SD=0.052). Data for the 4.3 percent slope yielded an average n value of 0.15 (SD=0.041). The n values from the two slopes are not statistically different ($p < 0.05$, Student's t test).

**Table 6-2. Range of Data for Mountlake Terrace Biofiltration Swale**

| Date | Flow Rate (cfs)[1] | Velocity Range (feet/second) | Depth Range (feet) |
|---|---|---|---|
| September 10, 1991 | 0.55 | 0.34-0.95 | 0.08-0.38 |
| | 0.75 | 0.10-1.56 | 0.08-0.40 |
| October 21, 1991 | 0.33 | 0.00-0.29 | 0.07-0.18 |
| | 0.42 | 0.15-0.46 | 0.12-0.22 |
| | 0.51 | 0.18-0.60 | 0.16-0.28 |

Footnotes:
1. From data logger in H-flume

The three flow rates used during the trials were 0.33 cfs, 0.43 cfs and 0.51 cfs, as given by the data logger. Accuracy of the Marsh-McBurney velocity measurements, used to check the results obtained using Method 1, was seen to increase as flows increased. The check was made by adding the individual discharges, calculated using the incremental velocity data, from each of the six hub cells. Good agreement was seen only for the highest discharge, where the sum of the small discharges was 0.43 cfs compared to the data logger's calculation of 0.51 cfs.

**Table 6-3. Calculated Manning's n Values for Mowed Swale Observations Using Method 1, October 21, 1991**

| SECTION | FLOW | SLOPE | MANNING "n" | | SECTION | SLOPE | MANNING "n" | | Average n for flow conditions |
|---|---|---|---|---|---|---|---|---|---|
| | cfs | % | Team A | Team B | | % | Team A | Team B | |
| A1-F1 | 0.33 | 3.25 | 0.09 | 0.07 | A4-F4 | 4.3 | 0.13 | 0.10 | 0.1225 |
| A2-F2 | 0.33 | 3.25 | 0.15 | 0.14 | A5-F5 | 4.3 | 0.11 | 0.11 | |
| A3-F3 | 0.33 | 3.25 | 0.14 | 0.14 | A6-F6 | 4.3 | 0.08 | 0.21 | |
| A1-F1 | 0.42 | 3.25 | 0.14 | 0.15 | A4-F4 | 4.3 | 0.18 | 0.19 | 0.1608 |
| A2-F2 | 0.42 | 3.25 | 0.20 | 0.19 | A5-F5 | 4.3 | 0.16 | 0.17 | |
| A3-F3 | 0.42 | 3.25 | 0.22 | 0.10 | A6-F6 | 4.3 | 0.11 | 0.12 | |
| A1-F1 | 0.51 | 3.25 | 0.18 | 0.14 | A4-F4 | 4.3 | 0.23 | 0.21 | 0.1983 |
| A2-F2 | 0.51 | 3.25 | 0.22 | 0.22 | A5-F5 | 4.3 | 0.19 | 0.18 | |
| A3-F3 | 0.51 | 3.25 | 0.25 | 0.25 | A6-F6 | 4.3 | 0.15 | 0.16 | |
| Average n for 3.25% slope conditions | | | 0.166 (SD=0.052) | | Average n for 4.3% slope conditions | | 0.15 (SD=0.04) | | |

| Table 6-4. Manning's n Averages, Variances, and t-test Results for Mowed Swale Observations | | | | |
|---|---|---|---|---|
| Parameter | Average n | SD | Sample Size | Conclusions |
| | | | | Teams A and B |
| Team A | 0.163 | 0.0447 | 18 | not different |
| Team B | 0.153 | 0.0447 | 18 | t=0.67* |
| | | | | Slopes |
| 3.25% Slope | 0.1661 | 0.052 | 18 | not different |
| 4.3% Slope | 0.15 | 0.0412 | 18 | t=0 .49* |
| | | | | Flows 1, 2, and 3 |
| Flow 1—0.33 cfs | 0.1225 | 0.0361 | 12 | different |
| Flow 2—0.43 cfs | 0.1608 | 0.0361 | 12 | different |
| Flow 3—0.51 cfs | 0.1983 | 0.0412 | 12 | p=0.0001** |

* If t > 2.23, the null hypothesis of no difference is rejected; If t < 2.23, the null hypothsis of no difference is accepted

**p value using ANOVA, F statistic

As can be seen from Table 6-4, the average n values differ with different discharge values. From the lowest discharge rate to the highest, the average n values are 0.123, 0.161, and 0.198, respectively. These values were found to be statistically different ($p < 0.0001$: ANOVA F statistic).

The Manning's n value calculated using Method 1, averaging all flow rates, would be 0.161 (SD=0.048). However, it is not technically valid to average all values since the F test found the n values for different flow rates to be statistically different. The value for the highest flow rate, 0.198, is considered to be most accurate, based on the better agreement between the two methods of flow estimation described above.

### Method 2 Results—Incremental Velocity Data (6-Inch Grass Height)

Table 6-5 presents velocity measurements for the three flow conditions obtained from the King County velocity meter, corrected using the curve given in Figure 6-2. The Manning's n values based on incremental velocity, slope and depth measurements are presented in Table 6-6. Using this method, the average n values for the three flow rates are very similar. From the lowest discharge rate to the highest, the average n values are 0.193, 0.206, and 0.192, respectively. The n values from the three flow rates are, however, statistically different (ANOVA, F statistic, $p < 0.001$).

As with Method 1, a check was made between the velocity calculated from the data logger and that measured from the velocity meters (corrected for error). Also with Method 1, best agreement was found at the highest flow rate.

## Table 6-5. Depth and Velocity Measurements

King County Flow Meter: J. Coon
Shown with corrected velocity from calibration curve, October 21, 1991

UPPER SWALE

| HUB I.D. | FLOW RATE | SLOPE | DEPTH FT. | CORR. VEL. (FT/SEC) |
|---|---|---|---|---|
| A2 | 1 | 0.027 | 0.16 | 0.41 |
| A2 | 2 | 0.027 | 0.19 | 0.64 |
| A2 | 3 | 0.027 | 0.25 | 0.94 |
| B1 | 1 | 0.036 | 0.15 | 0.35 |
| B1 | 2 | 0.036 | 0.20 | 0.39 |
| B1 | 3 | 0.036 | 0.24 | 0.54 |
| B2 | 1 | 0.029 | 0.16 | 0.41 |
| B2 | 2 | 0.029 | 0.19 | 0.64 |
| B2 | 3 | 0.029 | 0.25 | 0.94 |
| B3 | 1 | 0.031 | 0.15 | 0.35 |
| B3 | 2 | 0.031 | 0.20 | 0.39 |
| B3 | 3 | 0.031 | 0.24 | 0.54 |
| C1 | 1 | 0.036 | 0.14 | 0.33 |
| C1 | 2 | 0.036 | 0.19 | 0.32 |
| C1 | 3 | 0.036 | 0.22 | 0.36 |
| C2 | 1 | 0.033 | 0.15 | 0.28 |
| C2 | 2 | 0.033 | 0.20 | 0.33 |
| C2 | 3 | 0.033 | 0.24 | 0.36 |
| C3 | 1 | 0.030 | 0.14 | 0.33 |
| C3 | 2 | 0.030 | 0.19 | 0.32 |
| C3 | 3 | 0.030 | 0.22 | 0.36 |
| D1 | 1 | 0.034 | 0.13 | 0.36 |
| D1 | 2 | 0.034 | 0.19 | 0.41 |
| D1 | 3 | 0.034 | 0.22 | 0.45 |
| D2 | 1 | 0.032 | 0.17 | 0.27 |
| D2 | 2 | 0.032 | 0.23 | 0.28 |
| D2 | 3 | 0.032 | 0.27 | 0.26 |
| D3 | 1 | 0.030 | 0.13 | 0.36 |
| D3 | 2 | 0.030 | 0.19 | 0.41 |
| D3 | 3 | 0.030 | 0.22 | 0.45 |
| E1 | 1 | 0.033 | 0.07 | 0.17 |
| E1 | 2 | 0.033 | 0.13 | 0.34 |
| E1 | 3 | 0.033 | 0.17 | 0.44 |
| E2 | 1 | 0.036 | 0.16 | 0.42 |
| E2 | 2 | 0.036 | 0.22 | 0.44 |
| E2 | 3 | 0.036 | 0.24 | 0.43 |
| E3 | 1 | 0.032 | 0.07 | 0.17 |
| E3 | 2 | 0.032 | 0.13 | 0.34 |
| E3 | 3 | 0.032 | 0.17 | 0.44 |
| F2 | | 0.087 | 0.07 | N/A |
| F3 | | 0.087 | 0.17 | 0.08 |

LOWER SWALE

| HUB I.D. | FLOW RATE | SLOPE | DEPTH FT. | CORR. VEL. (FT/SEC) |
|---|---|---|---|---|
| A5 | 1 | 0.042 | 0.06 | N/A |
| A5 | 2 | 0.042 | 0.13 | 0.30 |
| A5 | 3 | 0.042 | 0.18 | 0.41 |
| B4 | 1 | 0.048 | 0.13 | 0.34 |
| B4 | 2 | 0.048 | 0.19 | 0.30 |
| B4 | 3 | 0.048 | 0.24 | 0.36 |
| B5 | 1 | 0.040 | 0.16 | 0.31 |
| B5 | 2 | 0.040 | 0.23 | 0.34 |
| B5 | 3 | 0.040 | 0.28 | 0.34 |
| B6 | 1 | 0.036 | 0.08 | N/A |
| B6 | 2 | 0.036 | 0.13 | 0.28 |
| B6 | 3 | 0.036 | 0.17 | 0.37 |
| C4 | 1 | 0.045 | 0.14 | 0.28 |
| C4 | 2 | 0.049 | 0.21 | 0.28 |
| C4 | 3 | 0.049 | 0.25 | 0.35 |
| C5 | 1 | 0.036 | 0.11 | 0.33 |
| C5 | 2 | 0.036 | 0.18 | 0.32 |
| C5 | 3 | 0.036 | 0.22 | 0.37 |
| C6 | 1 | 0.045 | 0.14 | 0.32 |
| C6 | 2 | 0.045 | 0.17 | 0.38 |
| C6 | 3 | 0.045 | 0.22 | 0.50 |
| D4 | 1 | 0.038 | 0.15 | 0.33 |
| D4 | 2 | 0.038 | 0.22 | 0.40 |
| D4 | 3 | 0.038 | 0.27 | 0.42 |
| D5 | 1 | 0.034 | 0.12 | 0.33 |
| D5 | 2 | 0.034 | 0.16 | 0.41 |
| D5 | 3 | 0.034 | 0.20 | 0.57 |
| D6 | 1 | 0.054 | 0.10 | 0.31 |
| D6 | 2 | 0.054 | 0.15 | 0.31 |
| D6 | 3 | 0.054 | 0.20 | 0.37 |
| E4 | 1 | 0.040 | 0.12 | 0.45 |
| E4 | 2 | 0.040 | 0.20 | 0.45 |
| E4 | 3 | 0.040 | 0.26 | 0.46 |
| E5 | 1 | 0.036 | 0.11 | 0.54 |
| E5 | 2 | 0.036 | 0.20 | 0.57 |
| E5 | 3 | 0.036 | 0.24 | 0.67 |
| E6 | 1 | 0.050 | 0.10 | 0.38 |
| E6 | 2 | 0.050 | 0.15 | 0.47 |
| E6 | 3 | 0.050 | 0.22 | 0.70 |
| F4 | 3 | 0.087 | 0.20 | 0.40 |
| F5 | 1 | 0.031 | 0.14 | 0.24 |
| F5 | 2 | 0.031 | 0.20 | 0.28 |
| F5 | 3 | 0.031 | 0.24 | 0.33 |

Flow Rate: 1 = .330 cfs 2 = .419 cfs 3 = .508 cfs

**Table 6-6. Manning's n Values Using Method 2 for Mowed Swale Conditions**

| Flow Rate (cfs) | Number of Observations | Average Depth (SD) | Average Velocity (SD) | Manning's n (SD) |
|---|---|---|---|---|
| 0.33 | 26 | 0.132 (0.027 SD) | 0.336 (0.078 SD) | 0.193 (0.04 SD) |
| 0.42 | 27 | 0.184 (0.03 SD) | 0.382 (0.101 SD) | 0.206 (0.053 SD) |
| 0.51 | 27 | 0.227 (0.03 SD) | 0.472 (0.169 SD) | 0.192 (0.059 SD) |

The Manning's n value calculated using Method 2, averaging all flow rates, would be 0.20 (SD=0.045). However, as before, it is not technically valid to average all values since the F test found the n values to be different for different flow rates. The value for the highest flow rate, or 0.192, is considered to be most accurate, based on the better agreement between the two methods of flow estimation described. More detailed information is given in Appendix F.

### Method 3 Results: Dye Test Velocities (6-inch Grass Height)

At the lowest flow rate (0.33 cfs), the $V_{max}$ as determined by the dye test was not done for the intermediate flow rate of 0.42 cfs). The average velocities measured from the velocity meters, corrected for error, were 0.34 feet per second and 0.47 feet per second for the high and low flow, respectively. It is plausible the $V_{max}$ could be higher than the average as is the case for the higher flow rate. However, for the low flow case, the $V_{max}$ from the dye test, 0.26 feet per second, was lower than the average velocity of 0.34 feet per second from the corrected velocity meter data, an illogical result. Therefore, only the $V_{max}$ from the high flow case is considered reliable. If this $V_{max}$ (0.52 feet per second) is used to calculate a Manning's n, using average slope from the 18 swale hubs, as in Method 1, and an average hydraulic radius, the resultant n value is 0.192, which agrees very well with the values calculated using the other two methods.

### Discussion

Because of limitations in ability to measure velocity precisely at low flows, the most reliable data are from the highest flow trial (0.51 feet per second). The Manning's n values observed for this flow range from 0.192 to 0.198, using different methods of calculation. These values came from a swale that was infrequently mowed.

It is likely that different maintenance regimes would result in different grass blade densities. In general, thicker grass would be expected to increase resistance to flow, thus increasing the n value. Therefore it is recommended that further research be performed to determine the change of n value with grass blade density as a variable in grassy swales. It would be a relatively simple, though tedious, task to investigate grass blade densities from mowed swales and compare them with the densities measured in the test swale. It is also suggested that work is needed to determine the appropriate n value for vegetation other than grass.

### Unmowed Swale Condition Results

Since both methods 1 and 2 agreed closely for the mowed swale trial, data for the unmowed trial were only analyzed using Method 1. Table 6-7 shows the Manning's n values for the different slope and flow conditions during the September 10 trial. Results using depth measurements from the two different teams were not statistically different ($p=0.93$) (n values being 0.194 and 0.205), so observations from the two teams were combined to increase sample size.

The n values computed for the two swale slopes were 0.184 for the 3.25 percent slope and 0.215 for the 4.3 percent slope ($n=12$). More variability was seen in this data set, and although these values look different, the difference is not statistically significant ($p=0.66$).

Only two flows were measured in this trial, 0.55 cfs and 1.1 cfs. For the two flow conditions the n value was 0.235 (SD=0057) for the 0.55 cfs flow and 0.164 (SD=0.033) for the 1.1 cfs flow. The corresponding water depths for these flows averaged about 3.5 inches for the 0.55 cfs flow rate and about 4.3 inches for the 1.1 cfs flow rate. Table 6-8 summarizes n values, standard deviations and statistical conclusions for the unmowed trials.

As found above, the average n values for the two flow conditions were 0.235 for the first flow (0.55 cfs) and 0.164 for the second flow (1.1 cfs). These values were statistically different ($p < 0.0005$, Student's t-test). Although somewhat counterintuitive, two field observations provide a rationale for why the Manning's n might be lower at the higher flow. First, when velocities approached 0.93 feet per second, before the final water depth for the second flow case, the grass was laid flat against the bottom of the swale, and most of the water flowed over the top of the grass. Thus on average, less resistance would have been encountered than if the grass had remained erect or slightly bent. Secondly, channelization of the flow was observed at the higher flow rate. Thus paths of least resistance for the flow were formed, again decreasing resistance to flow through the swale.

**Table 6-7. Calculated Manning's n Values for Unmowed Swale Observations Using Method 1**

| SECTION | % SLOPE | FLOW (cfs) | MANNING "n" | | % SLOPE | FLOW (cfs) | MANNING "n" | | Average n for flow conditions |
|---|---|---|---|---|---|---|---|---|---|
| | | | TEAM A | TEAM B | | | TEAM A | TEAM B | |
| A1-F1 | 3.25 | 0.6 | 0.17 | 0.14 | 4.3 | 0.6 | 0.32 | 0.30 | 0.235 (SD=0.057) |
| A2-F2 | 3.25 | 0.6 | 0.24 | 0.25 | 4.3 | 0.6 | 0.27 | 0.27 | |
| A3-F3 | 3.25 | 0.6 | 0.19 | 0.29 | 4.3 | 0.6 | 0.19 | 0.19 | |
| A1-F1 | 3.25 | 1.1 | 0.12 | 0.12 | 4.3 | 1.1 | 0.20 | 0.22 | 0.164 (SD=0.405) |
| A2-F2 | 3.25 | 1.1 | 0.15 | 0.18 | 4.3 | 1.1 | 0.17 | 0.19 | |
| A3-F3 | 3.25 | 1.1 | 0.18 | 0.18 | 4.3 | 1.1 | 0.13 | 0.13 | |
| Average n for 3.25% slope conditions | | | 0.184 | | Average n for 4.3% slope conditions | | 0.215 | | |

**Table 6-8. Manning's n Averages, Standard Deviations, and t-test Results for Unmowed Swale Observations**

| Parameter | Average n | SD | Sample Size | Conclusions |
|---|---|---|---|---|
| Team A | 0.1942 | 0.0583 | 12 | Teams A and B not different p=0.66 |
| Team B | 0.205 | 0.0608 | 12 | |
| 3.25% Slope | 0.184 | 0.0539 | 12 | Slopes 1 and 2 not different p=0.93 |
| 4.3% Slope | 0.2149 | 0.0656 | 12 | |
| Flow 1—0.6 cfs | 0.235 | 0.0574 | 12 | Flows 1 and 2 different p=0.0005 |
| Flow 2—1.1 cfs | 0.164 | 0.0332 | 12 | |

The observed decrease in the n value as water depths exceed grass height was also reported by Kao and Barfield (1978). Their work indicates that the Manning's n value is proportional to both the square of the flow velocity and the depth of blade submergence. As the velocity and depth of blade submergence increase, the n value increases until the vegetation is completely submerged. The n value then decreases.

Also interesting is the fact that the Manning's n observed for the 0.55 flow rate for the unmowed swale (n=0.235), was higher than that observed for the 0.51 flow rate for a grass height of 6 inches (n=0.198 using Method 1 and 0.192 using Method 2). Again, field observation may provide a rational for this observation. At a flow rate of about 0.5 feet per second, the grass was observed to be bent over. Field notes showed that for an average swale section, anywhere from 40 percent to 60 percent of the grass was no longer standing above the water but bent over within the water column (as opposed to flattened). If the grass were longer (12 inches as opposed to 6 inches), there would be more grass blade surface in contact with the water causing more resistance to flow, and thus the Manning's n would be expected to be higher up to the point where flows were so high that the grass was flattened. These data may indicate that the Manning's n used to design an unmowed swale should be higher than for a mowed swale. There are uncertainties, however, about the application of this data to other situations, since some trampling of the grass occurred during the test which may or may not be representative of other unmaintained swales.

## CONCLUSIONS AND RECOMMENDATIONS

This study has shown that Manning's n does not vary with small changes in slope, but does vary with flow rate. Some variation was also seen with grass height (6 inches versus 12 inches). Table 6-9 summarizes the various Manning's n values calculated from the field observations for both the mowed (6-inch grass) and unmowed (12-inch grass) conditions. For the mowed trials, three flow rates between 0.33 and 0.51 cubic feet per second were used. Because of limitations in ability to measure velocity precisely at low flows, the most reliable data are from the highest flow trial (0.51 cubic feet per second). The Manning's n values observed for this flow range from 0.192 to 0.198. Considering uncertainties involved in this study, and erring on the conservative side, a Manning's n of 0.20 is recommended for stormwater treatment applications.

**Table 6-9. Average Mannings's n Values of Mowed and Unmowed Swale Observations Using Different Methods of Calculation**

| Method | 0.33 cfs | 0.43 cfs | 0.51 cfs | 0.6 cfs | 1.1 cfs | Average |
|---|---|---|---|---|---|---|
| Mowed Swale Conditions | | | | | | |
| Method 1 | 0.1225 | 0.161 | 0.198 | — | — | 0.161 |
| Method 2 | 0.193 | 0.206 | 0.192 | — | — | 0.197 |
| $V_{max}$ | — | — | 0.192 | — | — | — |
| Unmowed Swale Conditions | | | | | | |
| Method 1 | — | — | — | 0.235 | 0.164 | 0.2 |

In applying this information, the user should be aware that this Manning's n of 0.20 is for a swale with a 6-inch grass height, having grass blade densities averaging from 600 blades/ft$^2$ in the upper swale to 1,600 blades/ft$^2$ in the lower swale. The swale had infrequent maintenance (mowing and other lawn maintenance activities such as aeration and fertilization). It is not known with certainty if or how much the Manning's n value might vary for denser grass.

For regularly mowed swales, grass is likely to be denser, and hence the Manning's n value may be higher than the 0.20. Therefore, it is recommended that the Manning's n value of 0.20 found in this study be adopted as the *minimum* value for grass swale design. More work should be done to investigate Manning's n for regularly mowed grass. Work is also needed to determine the appropriate n value for vegetation other than grass.

Before mowing, when grass was about 12 inches, the Manning's n calculated for the same swale was 0.235. Although other factors may have also influenced some of the difference observed, when bent over, longer grass would likely cause a higher resistance factor than shorter grass. Therefore it seems reasonable to apply this higher Manning's n value in situations where swales are infrequently maintained, such as for rural roads. However, in general, regular mowing of swales is strongly recommended, as will be discussed more fully in Section 7.